Propellant Tank Thermodynamics during Mars Orbiter Mission

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***Abstract*— India's mission to Mars was a huge success considering first interplanetary endeavor undertaken by the country. As per the mission plan, LAM and eight AOCS engines were operated on blow-down mode during MOI. The propellant tank pressure falls continuously due to blow down operation, resulting ullage cooling. This may lead to propellant freezing if ullage temperature drops below freezing point. Detailed mathematical model of propellant tank is developed to understand the transient thermodynamic behavior of propellants inside the tank for various scenarios of engine operation. The evolution of pressure and temperature in MON-3 tank are well corroborated with in house blowdown experiments and TMI phase of MOM. Further study is carried out to determine the effect of initial ullage volume and onboard heaters on thermodynamic condition inside propellant tank during blow down.**

Key Words: MOM, MON-3 Tank, Pressure, TMI

NOMENCLATURE

t	Time (s)
Cp	Specific heat at constant pressure (J/kgK)
m	Resident mass (Kg)
k	Thermal conductivity (W/m K)
M_M	Molecular weight of MON-3 (kg/mole)
M_H	Molecular weight of Helium (kg/mole)
P	Tank Pressure (Pa)
D_{MH}	Diffusion coefficient (m+/s)
Gr	Grashoff Number
Pr	Prandtl Number
Re	Reynold Number
a	Acceleration due to gravity (m/s^2)
Q	Heat (J)
h	heat transfer coefficient (W/m^2K)
H	Enthalpy (J/kg)
A	Area of heat transfer (m^2)
Nu	Nusselt Number
T	Temperature (K)
M	Molecular weight (kg/mole)
hfg	Latent heat of vaporization (J/K)
x	Tank height (m)

Greek symbols:

ρ	Density (kg/m3)
β	Coefficient of Thermal Expansion (K^{-1})
μ	Coefficient of viscosity (kg/ms)
ν	Kinematic Viscosity (m^2/s)

Subscripts

a	Ambient
int	Interface
l	Liquid
u	Upstream
d	Downstream
t	Total
Mu	MON-3 in Ullage
Mi	MON-3 at interface
Hu	Helium in Ullage
Hi	Helium at Interface
s	Tank outer surface
f	Fluid
v	Vapour
w	Tank inner wall

Abbreviations:

MOM	Mars Orbiter Insertion
MOI	Mars Orbit Insertion
TMI	Trans Mars Insertion
LAM	Liquid Apogee Motor
AOCS	Attitude and Orbit Control System
MON-3	Di-Nitrogen Tetroxide with 3% Nitric Oxide

I. INTRODUCTION

India's first interplanetary mission, Mangalyaan or Mars Orbiter Mission (MOM), was launched into Elliptical Parking Orbit (EPO) over Earth using PSLV C25 launcher on 5th November 2013. After series of orbit raising maneuvers, the orbiter was injected to Helio Centric Orbit on 1st December 2013 through Trans Mars Insertion (TMI) operation. On 24th September 2014, Mangalyaan came across the Sphere of Influence of Mars, upon which the orbiter was retro-fired to be captured to Mars orbit through the operation called Mars Orbit Insertion (MOI). Maneuvers such as orbit raising, TMI and MOI were carried out using Liquid Apogee Motor (LAM) engine with the help of eight Attitude and Orbit Control System (AOCS) thrusters, which are used for minor course correction and station keeping of the orbiter. The fuel, Mono Methyl Hydrazine (MMH), and the oxidizer, MON-3, are fed into LAM and AOCS thrusters at constant pressure under nominal operation, which is called regulated mode. Constant propellant pressure is ensured by pressurizing the respective propellant tanks with gaseous Helium stored on-board.

For the safety of the mission during MOI, it was decided to carry out the operation under blow down mode of the propellants. During blow down mode, propellant tanks are not pressurized while the propellants are being fed to the thruster. This causes decrease in propellant tank pressure, which in turn causes gradual reduction in thrust output. In order to gain maximum retro-thrust from the available propellant resources,

LAM and eight AOCS thrusters were fired simultaneously, which enabled the injection of the orbiter nearer to the desired orbit over Mars. In the likelihood of non-operation of LAM, a contingency plan was also designed for retro-firing the orbiter using eight AOCS alone, under propellant blow down mode. Since the requirement of propellant tank draining under blow down mode was envisaged only after the TMI operation, propellant tank thermodynamics and its implications on orbiter propulsion system had to be assessed quickly and accurately.

Current study focuses on developing a transient, two-phase, thermodynamic flow model of MON-3 tank to capture the propellant thermodynamic behavior during blow down operation. The model is able to determine the pressure and temperature evolution inside the tank for different propellant flow system.

II. FORMULATION AND SOLUTION METHODOLOGY

Model for simulating the pressure and temperature of MON-3 tank is developed in SINDA/FLUINT flow and thermal simulator. Figure 1 shows the schematic of the flow and thermal model developed for the analysis.

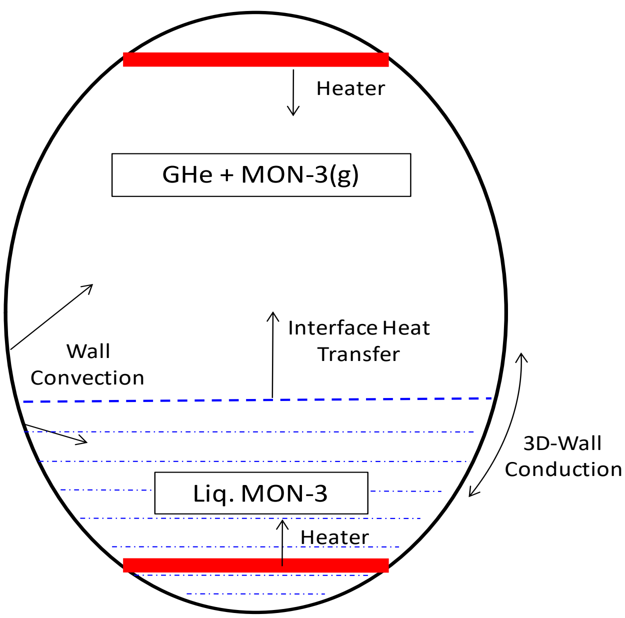

Fig 1. Schematic of the model used for simulations

The heat transfer modes and resulting thermodynamic effects occurring inside the tank are considered in the model, namely interface heat and mass transfer, fluid to wall convection, 3-D wall conduction, evaporation and condensation, multi species in ullage and liquid draining. The percentage of MON-3 vapors in ullage containing GHe is input based on the saturation conditions at the respective initial temperature. Additionally, ambient convection heat transfer over the tank insulation is also considered for ground test simulation cases. The two heaters present on tank wall one each at ullage and liquid side. A detailed description of the heat and mass transfer modes considered in the model is discussed in the following sections, A to G.

A. *Conservation of Mass*

The net mass flow from a fluid node is equated to the rate of change of mass in the control volume as shown below.

$$\frac{dm}{dt} = \dot{m}_u - \dot{m}_d \tag{1}$$

Conservation of mass is ensured at each fluid node during each time-step of transient simulation.

B. *Conservation of Energy*

The energy conservation equation is expressed on the basis of the first law of thermodynamics. The rate of increase of internal energy in the control volume is equal to the difference between the rate of energy transport into the control volume and the rate of energy transport from the control volume. The energy conservation equation based on enthalpy can thus be written as below:

$$\frac{dU}{dt} = (H_u \dot{m}_u - H_d \dot{m}_d) + \dot{Q} \tag{2}$$

where Q, represents heat transfer between tank wall and fluid with heat transfer coefficient ‘h’, described later in this section.

$$Q = hA(T_s - T_f) \tag{3}$$

C. *Equation of State*

Thermodynamic variables are calculated using real fluid state equation with compressibility factor, Z, being an input from NIST database [1].

$$P = Z.\frac{m}{V}.\frac{R}{M}.T \tag{4}$$

D. *Heat transfer across interface*

The model is used to analyze the evolution of fluid temperature inside the tank considering conduction, convection, heat and mass transfer across the interface. A schematic of the cryogenic tank showing various heat transfer mechanism is depicted in Fig. 1. Heat, from ullage to bulk liquid, transfers through interface. However, the heat transfer from ullage to interface and interface to liquid are equal. Heat transfer from the interface to liquid is expressed as:

$$\frac{dQ_{int-l}}{dt} = h_{int-l} A_{int} \frac{d\Delta T_{int-l}}{dt} \tag{5}$$

The heat transfer from the ullage gas to interface is due to convection. Since, diffusing or condensing constituent carries

its own individual enthalpy, there is an additional heat transfer across interface due to mass transfer of these species. Effective heat transfer from the ullage gas to interface is expressed as:

$$\frac{dQ_{v-int}}{dt} = h_{u-int} A_{int} \frac{d\Delta T_{v-int}}{dt} + H \frac{dm}{dt} \tag{6}$$

m and H are mass and enthalpy of fluid transfer across interface. m is positive for condensation and negative for vaporization of the liquid. It has been assumed that the heat transfer is due to natural convection with the heat transfer coefficient being expressed by the correlations as below [2].

$$h = K_H C \frac{k_l}{l_s} Ra^n \tag{7}$$

where:

$$Ra = Gr.Pr \tag{8}$$

and

$$Gr_x = \frac{g\beta(T_w - T_b) l_s^3}{\upsilon^2} \tag{9}$$

$$Pr = \frac{\mu_l Cp_l}{k_l} \tag{10}$$

Constant 'C' is 0.54 and 0.27 for heat transfer from ullage to interface and interface to liquid respectively. n = 0.25 and 'KH' (heat transfer adjustment factor) is set to 1.0. The length scale 'ls' is set to the diameter of the tank.

E. Mass transfer across liquid vapor interface

The presence of helium in the ullage results in diffusion and mass addition of gaseous MON-3 in the GHe and MON-3 mixture. To calculate the resultant mass transfer (m) due to condensation and evaporation, the formulation of the Chilton-Coulburn analogy [3] is used as given below:

$$\frac{h_{\text{int}-l}}{m/\left(\rho_{Mu} - \rho_{Mi}\right)} = \left[\frac{Pt}{P_{Hu}} . \rho_{Hu} . \frac{\ln\left(\frac{\rho_{Hi}}{\rho_{Hu}}\right)}{(\rho_{Hi} - \rho_{Hu})} \right]^{-1} \left[\rho . C_p . \left(\frac{K}{D_{MH}} \right)^2 \right]^{1/3} \tag{11}$$

Method of Fuller, Schettler and Giddings analogy [4] is used for estimating diffusion coefficient (DMH) through binary mixtures and the expression is shown below:

$$D_{MH} = \frac{10^{-3} T_v{}^{1.75} [(M_{Mu} + M_{Hu})/(M_{Mu} M_{Hu})]}{P\left[(\Sigma v_{Mu})^{1/3} + (\Sigma v_{Hu})^{1/3}\right]^2} \tag{12}$$

ΣvMu and ΣvHu are diffusion volume [5] for MON-3 and Helium respectively.

F. Heat transfer from wall to fluid

The heat transfer from wall to ullage gas is expressed as:

$$\frac{dQ}{dt} = hA_{f-w}(T_w - T_f) \tag{13}$$

It has also been assumed that the heat transfer is due to natural convection and heat transfer coefficient is expressed as:

$$h = 0.508 \frac{k}{l_s} \mathrm{Pr}^{0.5} \left(0.952 + \mathrm{Pr}\right)^{-0.25} Gr^{0.25} \tag{14}$$

where ls is the height of the tank at the particular point at which h is calculated.

G. Heat transfer from ambient

Coefficient of convective heat transfer on tank surface is calculated by using Churchill and Bernstein [2] based formulation based. Heat transfer from outside is expressed below.

$$\frac{dQ}{dt} = hA_s \frac{d\Delta T_{a-s}}{dt} \tag{15}$$

$$h = \left(0.3 + \frac{0.62 Re^{0.5} \mathrm{Pr}^{0.33}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{\frac{2}{3}}\right]^{0.25}} \left[1 + \left(\frac{Re}{28200}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}} \right) . \frac{k_a}{D} \tag{16}$$

$$Re = \frac{\rho_a v_a D}{\mu_a} \tag{17}$$

To calculate heat transfer from ambient to the tank wall, three dimensional transient heat conduction equations are solved considering the variation of thermal conductivity of the insulation with temperature. Three-dimensional transient heat conduction equation is given by following expression considering k as a function of temperature:

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=\frac{\rho Cp}{k(T)}\cdot\frac{\partial T}{\partial t} \quad (18)$$

III. RESULTS AND DISCUSSION

The mathematical model is used to simulate the pressure and temperature evolution inside propellant tank during blowdown phase of TMI, in-house experiments and MOI. The model is first validated with TMI data and followed by in-house experiment data after understanding the effect of ullage volume on pressure evolution. Subsequently, possibility of MON-3 freezing during blow down operation is investigated, followed by the analysis of MON-3 tank with contingency plan when LAM engine is in passive mode. Further analysis shows the effectiveness of onboard heaters on tank pressure evolution during blowdown of contingency plan. The measured and simulated plots for each case are discussed as below.

A. Trans Mars Insertion (TMI) Phase

TMI phase of MOM was carried out to transfer Mangalyaan from Earth Parking Orbit to Helio Centric orbit. During TMI, the MON-3 tank was briefly under blow down mode for 200s prior to regulated mode of engine operation. The tank pressure and temperature data during blow down mode of TMI is used to validate the mathematical model. The analysis carried out for the TMI scenario starts from blow-down commencement and showed close match with the on-board observations as seen in Fig. 2. The blow-down starts at local time scale of 233s and continue up to 436s after which tank pressurization using GHe maintains the tank pressure. The fall in tank pressure and wall temperature measured on-board were 1.2 bar and 2.7K respectively.

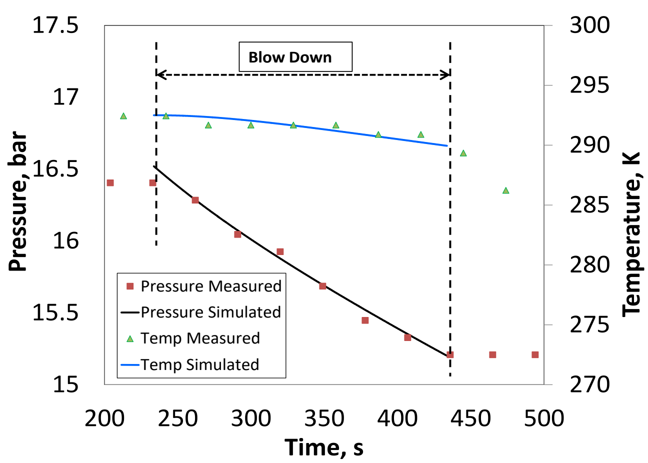

Fig. 2. Pressure and wall temperature in MON-3 tank for TMI phase of MOM (Simulation vs. Measurement)

It can be seen from Fig. 2 that the simulation results using mathematical model of MON-3 tank are in close agreement with measurement data during TMI. Thus, the model can be deemed corroborated with blow down phase of TMI.

B. Ground Simulation Test

In-house experiments were carried out prior to the MOI operation to determine the pressure and temperature evolution inside the propellant tank during blow down operation. The propellant tank used for ground experiment was not identical to the tank used for MOM. The experimental tank volume was about 50 liter lesser than the actual tank volume used for MOM.

The first ground blow down experiment was carried out similar initial ullage volume as in MON-3 tank at start of MOI. The propellant tank was in blowdown mode for lower duration of 1000s due to lower propellant volume in first experiment. Further experiment was carried out with lower initial ullage volume and higher liquid volume to achieve the blow down for longer duration. A numerical study was carried out, to bring out sensitivity of initial ullage volume on the evolution of pressure inside the MON-3 tank during blow down. The different cases with initial ullage volume of 150liter, 200liter, 250liter and 300litre were analyzed considering initial tank pressure of 16bar. Results of this study are shown in Fig. 3.

It can be seen from Fig. 3 that the reduction in initial ullage volume of the MON-3 tank results in faster tank pressure decay. The simulated tank pressure at 1000s is 12.2bar, 11.8bar, 11.1bar and 10.2bar for initial ullage volume of 300liter, 250liter, 200liter and 150litre respectively. It can be concluded that the changes in initial ullage volume has significant effect on the tank pressure decay profile and thereby, on the magnitude of final pressure.

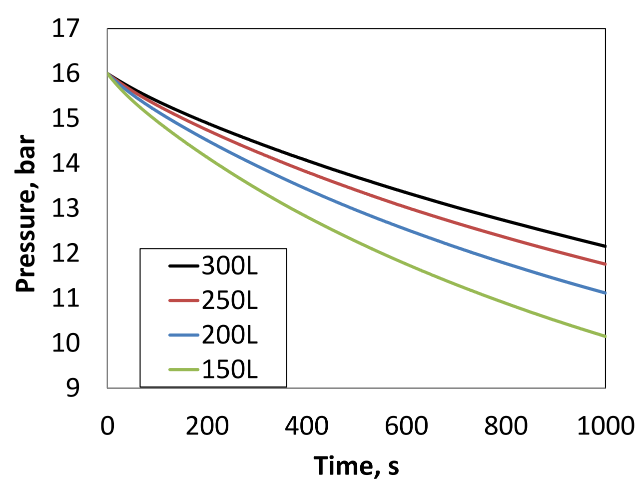

Fig. 3. Tank pressure evolution for different initial ullage volume

Further analysis was carried out to simulate experiment test conditions and validate the mathematical model with ground blow down test. Input conditions for the both the tests are shown in Table 1. The comparison of simulated results

with measured tank pressure evolution and surface temperature are shown in Fig 4, 5 and 6.

Table 1. Input conditions for experiments

Parameters	Test-1	Test-2
Initial temperature	300K	298K
Initial tank pressure	16.6 bar	16.4 bar
Initial ullage volume	250 liters	208 liters
Blow down duration	1000s	1800s

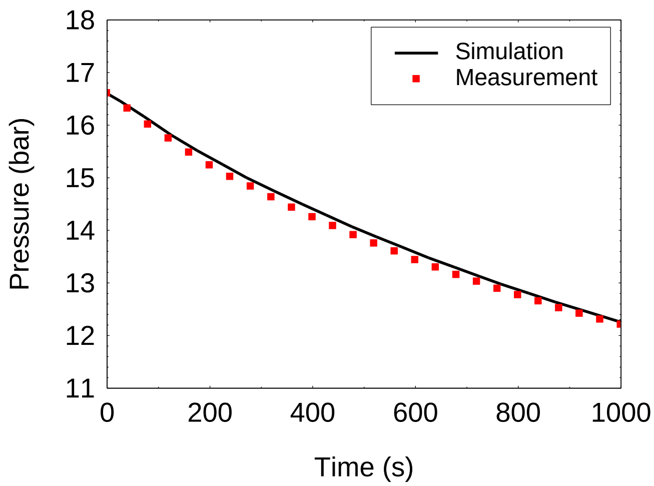

Fig.4. Tank Pressure during first experiment (Simulation vs. Measurement)

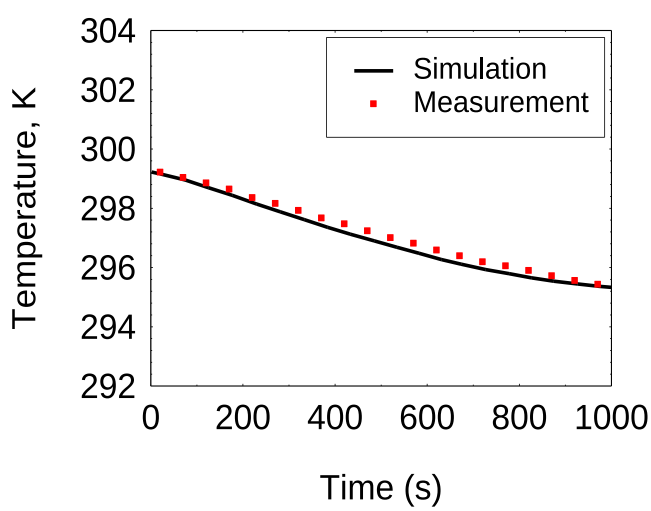

Fig.5. Ullage wall temperature during first experiment (Simulation vs. Measurement)

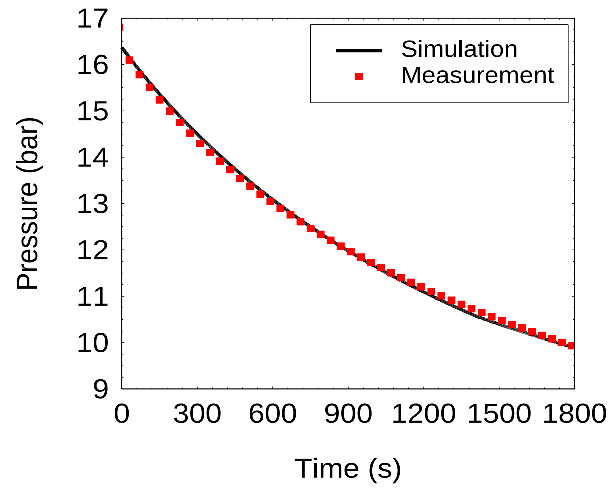

Fig.6 Tank Pressure during second experiment (Simulation vs. Measurement)

The simulated ullage pressure and tank wall temperature are very close with those measured during the test. Thus, the model is well corroborated with ground experimental tests.

C. Possibility of Propellant Freezing

The ullage gas in propellant tank expands during blow down operation which results in reduction in ullage temperature and pressure. Simultaneously, the cold ullage receives heat from ullage wall and liquid-vapor interface which counters the cooling effect of ullage due to blow down. MON-3 in ullage condenses when ullage temperature falls to saturation based on partial pressure, thereby releasing latent heat to ullage which further heats the ullage. For sufficiently high drain flow rates, the thermodynamic cooling of ullage due to gas expansion dominates which may lead to propellant freezing at liquid-vapor interface, if ullage temperature drops below freezing point during blow down.

The model is used to determine the ullage gas temperature during blowdown. The analysis is also carried out to determine the effect of on-board heaters (18W each) on gas temperature near to interface.

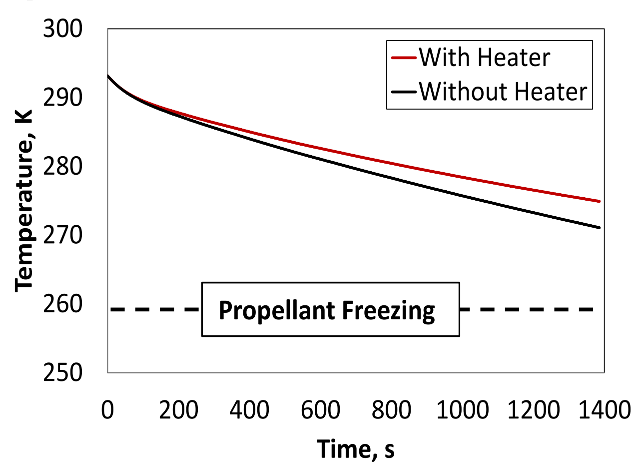

Fig.7. Ullage gas temperature during blow down phase of MOI

The ullage gas temperature profiles during blow down phase of MOI for heater on and off condition are shown in Fig.7. The minimum gas temperature during blow down is found to be 271K and 274.9K for heater off and on conditions respectively. Since the minimum gas temperature at liquid-vapor interface was always higher than MON-3 freezing point of 271K, the concern of propellant freezing was ruled out during blow down phase for existing configuration.

D. *Analysis for AOCS based MOI*

The AOCS alone configuration was studied considering the uncertainty in restarting LAM after nearly 300 days of inactivity. In order to realize satellite insertion in Mars orbit, the system has to retard to achieve a minimum required velocity. Since, AOCS thrust (22N) is much lower than LAM engine (440N), the required velocity will be achieved in longer duration of about 5500s against 1400s when LAM and 8 AOCS engines are in operation.

The propellant tank includes onboard heaters in ullage and liquid size as shown in Fig.1. It is to be noted that tank pressure as well as engine thrust can be increased by heating the tank during blowdown using onboard heaters.

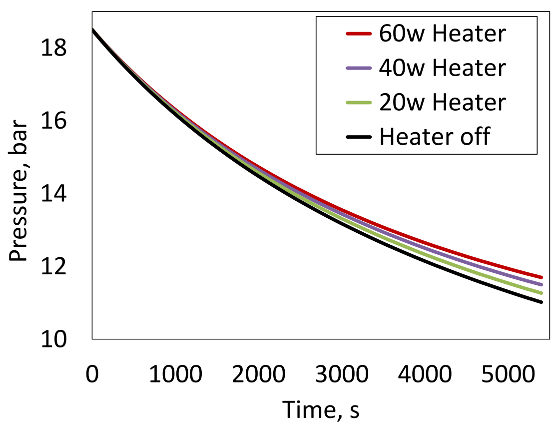

Fig.8. Tank pressure evolution with different heating condition for AOCS alone configuration

The study was carried out to determine the effectiveness of different tank heating on pressure evolution during blowdown. The different heating case of 20W, 40W and 60W were analyzed considering initial tank pressure of 18.5bar. It can be seen from Fig 8 that tank pressure reaches 11.0bar, 11.27bar, 11.49bar and 11.69bar at 5400s in case of no heating, 20W, 40W and 60W heating respectively.

IV. CONCLUSIONS

A two-phase thermodynamic model was developed to simulate pressure and temperature evolution inside MON-3 tank during blowdown operation. The model was well corroborated with in-house experimental data. Subsequently, simulation was carried out for blow down phase of TMI and simulated results were found to be very close to the measurements.

Further parametric studies are carried out to bring out the effect of initial ullage volume, onboard heaters on tank pressure evolution during blow down. The study is also conducted to rule out the possibility of propellant freezing during blow down phase of MOI. Following are the salient conclusions drawn from the analyses for a propellant tank with draining in blow mode.

1. The magnitude of initial ullage volume has a significant role on the pressure decay profile. Higher ullage volume results in lesser pressure fall.
2. Since engine thrust varies with the tank pressure, the overall thrust can be increased by keeping the tank pressure higher with the help of external on-board heaters. Though the use of external heaters is a viable option to raise the tank pressure, it should be limited due to the occurrence of other phenomenon such as rise in liquid temperature and boiling for high volatile propellants.
3. The study concludes that there exists no potential for freezing of MON-3 in the propulsion system of MOM during MOI. It is to be noted that the propellant can freeze in case of higher engine flow rate or longer blowdown period. The occurrence of propellant freezing during blowdown operation is a precarious scenario and should not be ignored during system design.

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